

SOME ASPECTS OF UNSTEADY SEPARATION

by

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Unsteady separation can be forced in a variety of ways and in this presentation two fundamental means will be considered, namely (1) the introduction of convected vorticular disturbances into the flow and (2) the influence of a specific type of three-dimensional geometry. In both situations a response of the viscous flow near the wall is provoked wherein the fluid near the surface abruptly focusses into a narrow region that erupts from the surface into the mainstream. In two-dimensional flows the eruption takes the form of narrow explosively-growing spike, while in three-dimensional situations, examples are presented which indicate that the eruption is along a narrow zone in the shape of a crescent-shaped plume. The nature of the three-dimensional flow near a circular cylinder, which is mounted normal to a flat plate, is also examined in this study. Here the three-dimensional geometry induces complex three-dimensional separations periodically. The dynamics of the generation process is studied experimentally in a water channel, using hydrogen bubble wires and a laser sheet, and the main features of the laminar regime through to transition are documented.

Discussion

Unsteady viscous-inviscid interactions between an effectively inviscid outer flow and a viscous region near a surface occur in a variety of important applications such as the flows occurring in turbomachinery and on moving airfoil surfaces. Many examples occur in quite different physical environments but nevertheless exhibit a common type of behavior. At a certain stage, a viscous layer near a wall, which has been hitherto passive and which to this point is well described by conventional boundary-layer theory, begins to develop strong outflows over a zone which is very narrow in the streamwise direction. As this eruptive behavior develops, it culminates in the ejection of boundary-layer fluid away from the wall into the outer inviscid flow. The process is known as an unsteady viscous-inviscid interaction; it is generally distinguished by the eruptive nature of the phenomenon as well as the fact that discrete "chunks" of vorticity are torn from the region near the surface and abruptly introduced into the outer flow.

Such unsteady interactions can be induced in a number of ways, one of which occurs whenever a vortex is convected close to a solid surface. A vortex near a solid wall induces a moving region of adverse pressure gradient on the viscous flow near the surface and, provided the vortex is near the wall for a sufficient period of time, all moving vortices will ultimately provoke a boundary-layer eruption. Well-documented examples include the flow induced near a ground-plane by aircraft-trailing vortices (Harvey and Perry, 1971), the boundary layer induced by a vortex ring moving toward a plane wall (Walker et al., 1987) and the so-called "secondary instability" of Goertler vortices that develop in the boundary layer on a concave wall (Ersoy and Walker, 1985). In all of these situations, recirculating eddies develop in the boundary layer near the wall as a consequence of the pressure distribution induced by the parent vortex. With the evolution of these secondary vortices, strong updrafts begin to develop and the boundary layer evolves rapidly toward interaction with the outer flow. The nature of the interaction is such that a boundary-layer eruption occurs in a focussed band which is narrow in the streamwise direction, with the result that the secondary eddies are ejected from the boundary layer into the external flow (Walker et al., 1987).

Similar processes occur within the turbulent boundary layer (Walker et al., 1989; Walker, 1989) wherein the flow in the region near the wall breaks down violently and intermittently. The breakdown process always initiates near a low-speed streak and results in a strong, unsteady viscous-inviscid interaction with the outer layer motion. Recent studies (Haji-Haidari, 1990; Smith et al., 1990, and Walker, 1990) show that the streaks and the eruptive behavior are due to moving hairpin vortices which are convected near the surface. This represents the fundamental regenerative process in a turbulent boundary layer where new vorticity from the wall region is continually introduced into the outer part of the boundary layer through intermittent eruptions of the wall layer.

One objective of the present work was to develop algorithms to compute the evolution of strongly interacting boundary-layer flows and to this end a model problem was considered, namely the unsteady boundary layer induced by a two-dimensional vortex above a plane wall in an otherwise stagnant fluid. A zone of recirculation in the boundary layer is soon produced due to the pressure field associated with the vortex (Walker, 1989), and strong updrafts then evolve on one side of the recirculating eddy. As the boundary-layer flow starts to focus toward an eruption, it is not possible to track the phenomenon using conventional numerical methods based on the Eulerian formulation of the flow problem and in this study Lagrangian methods were used. In the latter approach, the trajectories of a large number of individual fluid particles are evaluated and, as the boundary-layer focusses toward an eruption, the fluid

particles move naturally into the erupting region, which is consequently well-resolved. Some calculated results for displacement thickness are shown in Figure 1, which is taken from Peridier and Walker (1989). Initially, the displacement thickness grows progressively after the motion is initiated (from an impulsive start), with the greatest growth occurring near $x = 0.5$ near the recirculating secondary eddy, that develops in the boundary layer for $t > 0.28$. However, at around $t = 0.85$ a corner starts to appear in δ^* and very rapidly the boundary layer focusses into a "needle-like" eruption. The dynamics of this process, which are believed to be generic for all two-dimensional flows, will be discussed.

For moving three-dimensional vortices, the induced flow patterns near the wall are much more complex but a narrow, focussed eruption is also produced. Experimental studies of the flow provoked by a moving hairpin vortex will be presented. The hairpin vortex is created in an otherwise laminar boundary layer and the nature of the flow induced downstream is documented. It is found that a discrete eruption of fluid from the wall region is produced. In three-dimensions, the erupting boundary layer first appears in the shape of a crescent-like ridge and then rolls over into a secondary hairpin vortex. This behavior is essentially predicted by the general three-dimensional theory of unsteady separation recently described by Van Dommelen and Cowley (1990).

Lastly, the nature of the flow near a three-dimensional corner is investigated experimentally using the configuration depicted schematically in Figure 2. In this situation, horseshoe vortices are observed to form periodically upstream of the cylinder; as they are swept outboard of the cylinder, sharp eruptive responses from the flow near the wall are seen. The flow regime is investigated thoroughly using hydrogen bubble wire flow visualization as well as a laser sheet. The separation processes are very complex but can be understood in terms of the basic influence of a vortex on a viscous flow.

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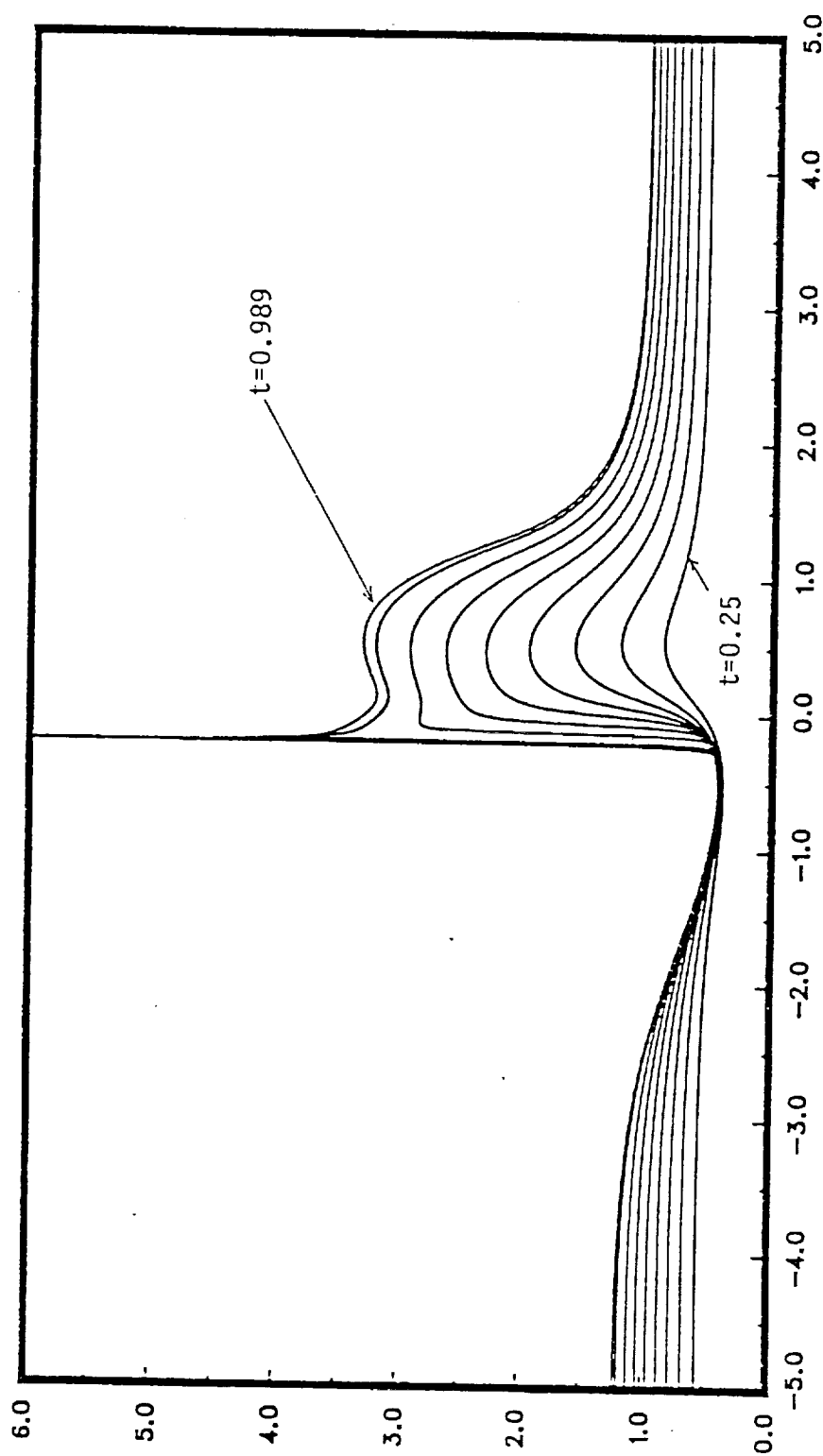


Figure 1: Temporal development of the displacement thickness δ^* ; plotted curves at $t = 0.25$, (0.10) , 0.95 and $t_s = 0.989$.

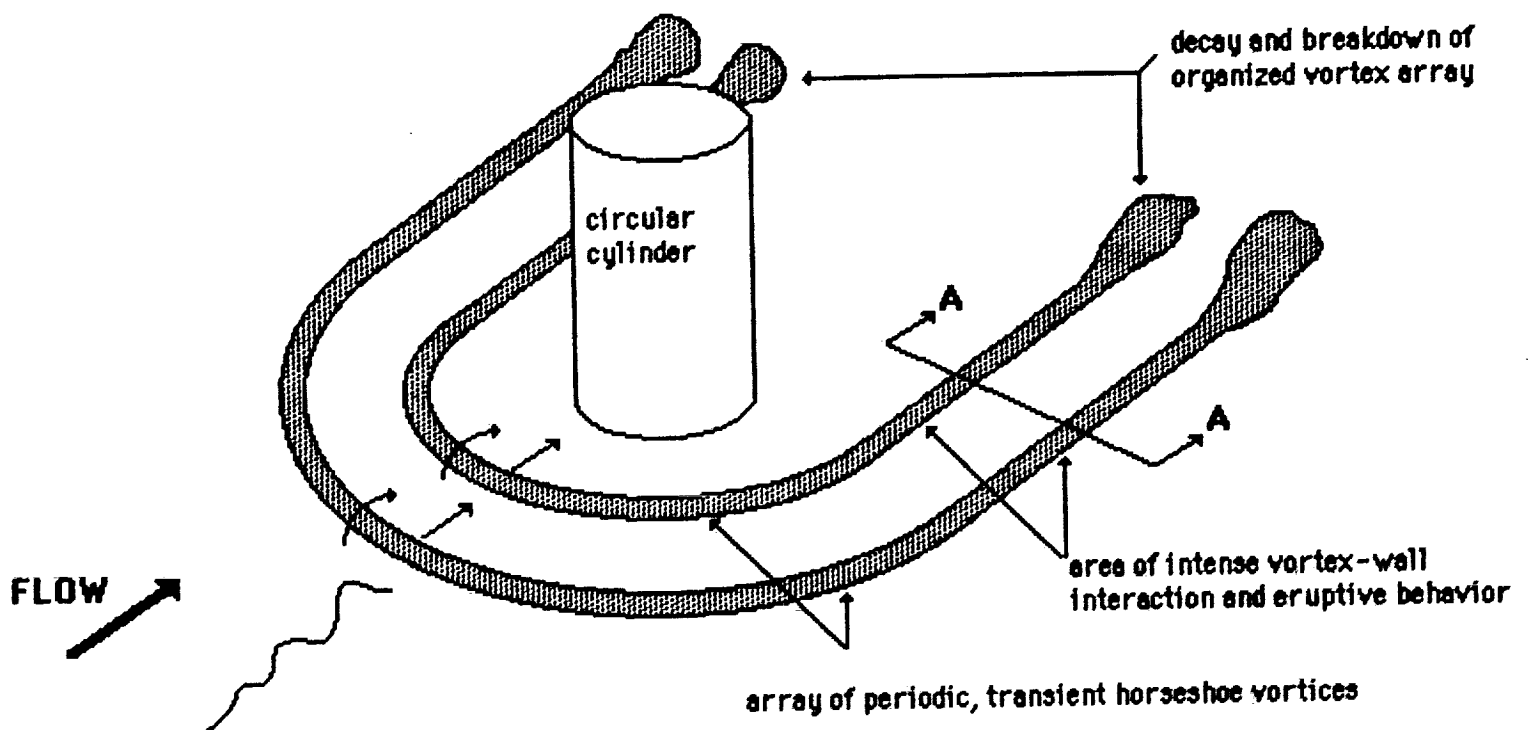
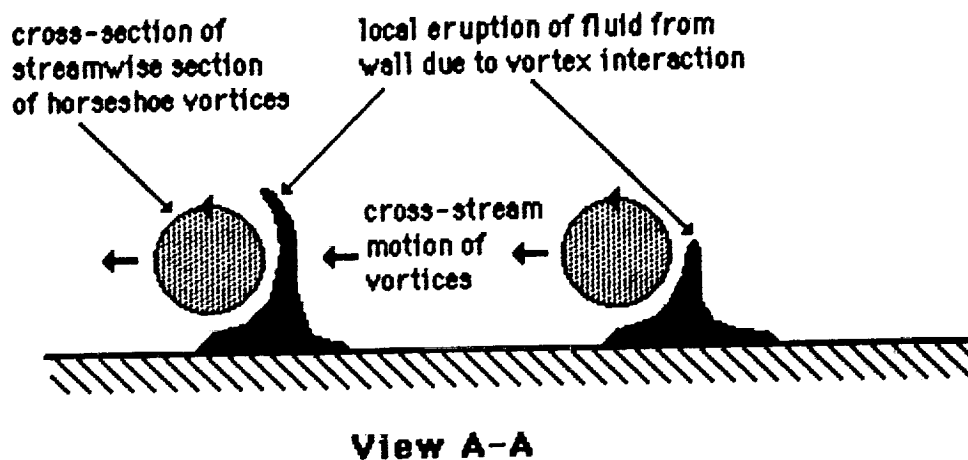


Figure 2: The development of a transient, three-dimensional horseshoe vortex array in a laminar boundary layer impinging on a cylinder. Note sharp eruptive behavior stimulated by vortex-wall interaction of the streamwise portion of the horseshoe vortices.